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Soybean Growth Response to Low Rates of Nitrogen Applied at Planting in the Northern Great Plains

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ABSTRACT

Cool and wet soils at the time of soybean [*Glycine max* (L.) Merrill] planting in the northern Great Plains may reduce early crop growth and retard nitrogen (N) fixation. Application of N as starter fertilizer may increase initial growth of soybean, but may also negatively impact N fixation when environmental conditions improve. The objective of this study was to evaluate the impact of low rates of N applied at planting on soybean N fixation and crop growth in the northern Great Plains. A field experiment (2000–2002) was established within a two-year corn [*Zea mays* (L.)] soybean rotation using a split-plot design with four replications. Whole plots were no-tillage (NT) and conventional tillage (CT) and the split plots were starter fertilizer (two sources × four rates) treatments. Nitrogen sources were either ammonium nitrate (AN) or urea (UR) each applied at 0, 8, 16, and 24 kg N ha^{-1}. Biomass in both 2000 and 2001 growing seasons increased significantly with increasing N rate at both growth stages (R1 and R7) and at the R1 stage in 2002. Ureide concentration and relative ureide decreased with increasing N rate at the R1 stage in all years, indicating a decrease in N fixation up to that point in crop development. This decrease in N fixation was not present at the R7 stage, but the significant increase in plant growth including yield was still present, indicating possibly that starter fertilizer can positively impact soybean production in the cool environmental conditions of the northern Great Plains. However, the positive impact on plant growth and yield is dependent on in-season environmental conditions and time of planting.

Keywords: soybean, nitrogen nutrition, relative ureide, biomass, starter fertilizer, nitrogen fixation

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INTRODUCTION

Over the past 10 years, soybean [*Glycine max* (L.) Merrill] acreage in Minnesota, South Dakota, and North Dakota has increased dramatically from 3.4 million hectares in 1992 to 5.5 million hectares in 2002, representing an increase of 40% (NASS, 1993, 2003). This increase in soybean planting, coupled with the establishment of soybean processing centers in the region, has caused producers to seek information to improve traditional management strategies. Because soybean is a legume and has the ability to fix N_2, fertilization with N (nitrogen) is not a common practice. Nitrogen fertilization has been evaluated as a method to improve protein and oil levels in seed (Starling et al., 1998; Flannery, 1986; Wesley et al., 1998). The majority of this research has taken place in the southern United States, with N application occurring in-season. Limited research has been performed evaluating the impact of low rates of N applied at planting on soybean grown in the northern United States.

Climatic conditions in the northern Great Plains cause soils to be cool and wet at the time of soybean planting. Researchers have concluded that proper environmental conditions (e.g., adequate water and proper temperature) must exist before soybean begins fixing N_2 (Hardy et al., 1971; Sorensen and Penas, 1978). Once these conditions are met, it could take an additional 14 d before fixation of atmospheric N begins (Hardy et al., 1971). Bergersen (1958) concluded that N fertilization before planting gave plants a better start, considering nodules were not present until 9 d after planting. Sorensen and Penas (1978) concluded that factors including soil temperature, water, and pH were the major causes of soybean response to applied N. Starling et al. (1998) found a small amount of N applied at planting in the southern United States stimulated early vegetative growth with dry-matter production at R1 (beginning flowering) increasing by 0.50 Mg ha^{-1} compared with no fertilizer. This increase in dry-matter production was coupled with an increase in canopy height and N concentration, although the N application decreased the number of nodules. Beard and Hoover (1971) found nodule numbers were reduced with application of N exceeding 56 kg ha^{-1} at planting, while N rates up to 112 kg ha^{-1} at flowering did not affect nodule formation. Nitrogen application rates had to exceed 168 kg ha^{-1} for nodule numbers to decrease.

Traditional methods for determining the impact of N fertilization on soybean fixation are destructive and labor intensive; they include counting soybean nodules and the acetylene reduction. An additional method is the ^{15}N A-value method developed by Fried and Broeshart (1975), which requires the use of ^{15}N labeled fertilizer and the use of a mass spectrometer for isotope ratio analysis, both of which could be cost prohibitive. An alternative would be to estimate relative ureide concentration utilizing above-ground plant material. Soybean is among a group of plant species known as ureide transporters. Ureides (allantoin and allantoic acid) are the primary form of N translocation in these plant species (Harper, 1987). Researchers have evaluated the potential of monitoring ureide concentration to estimate soybean N-fixation. McClure et al. (1980) evaluated the relative ureide content method against the precise ^{15}N A-value method and concluded that relative ureide content was a reliable indicator of N_2 fixation in soybean. Herridge and Peoples (1990) found that relative ureide content ([ureide/(ureide + nitrate)] × 100) was highly correlated to the amount of N derived from N fixation regardless of genotype or *Rhizobia* strain. Diatloff et al. (1991) reported that it was possible to utilize the ureide assay as an alternative to nodule counting, considering that relative ureide was significantly correlated with nodulation characteristics for samples collected at two sampling dates (R1 and R7). The objective of this study was to evaluate the impact of low rates of N applied at planting on soybean N fixation and crop growth.

MATERIALS AND METHODS

A field experiment was established at the Eastern South Dakota Soil and Water Research Farm near Brookings, SD, in a two-year corn (*zea mays*)-soybean rotation in the spring of 2000. The soil series at the site were a Barnes clay loam (fine-loamy, mixed, superactive, frigid Calcic Hapludolls) and a Vienna-Brookings complex (Vienna—fine-loamy, mixed, superactive, frigid Calcic Hapludolls; Brookings—fine-silty, mixed, superactive, frigid Aquic Hapludolls). The experimental design was a split-plot with four replications. Whole plots were tillage (NT and CT) and the split plots were a factorial combination of two starter N sources (AN and UR) and four N rates (0, 8, 16, and 24 kg N ha^{-1}). Conventional tillage was performed with a chisel plow in the fall of each year, followed by seedbed preparation in the spring using a field cultivator and cultivation performed in early July. The NT treatments were established with tillage ending in the spring of 2000 prior to soybean planting. Phosphorus (P) and potassium (K) were applied as starter to each plot at 17 kg P ha^{-1} as triple super-phosphate and 12 kg K ha^{-1} as KCl. All starter fertilizers (including N) were applied at planting in a band (5 cm below and 5 cm to the side of the seed furrow). Plots were 6 m by 15 m with 0.76 m row spacing.

Two adjacent plots were utilized for the experiment, and the corn/soybean rotation alternated between to the two plots every other year (soybean planted to one portion and the other portion planted to corn). Soybean and corn treatments were located on the same experimental plot every other year. The corn portion of the rotation received the same starter fertilizer treatments as those designated for the particular treatment for the soybean phase. An additional 85 kg N ha^{-1} was applied as AN side-dress at the V6 growth stage on all plots planted to corn. The previous crop before establishing the experiment in this location was wheat (*Triticum activum*).

A maturity group 1.0 soybean (Pioneer 91B01) was seeded at a rate of 590,000 seeds ha^{-1} (May 22, 2000; May 30, 2001; and May 15, 2002). All soybean plots regardless of tillage were planted using an eight-row John

Table 1
Planting, tillage, herbicide application, biomass, soil sampling and grain harvest dates, Brookings, SD, 2000–2002

	2000	2001	2002
Fall chisel†‡	Oct 27	Oct 24	Nov 5
Soil sampling	April 4	May 15	May 6
Seedbed tillage†	March 6	May 22	May 13
Planting	May 22	May 30	May 15
Herbicide application	June 20	June 28	June 12
Cultivation†	June 27	July 3	June 24
R1 biomass	July 6	July 12	July 1
R7 biomass	Aug 25	Sept 4	Aug 23
Grain harvest	Sept 18	Sept 28	Sept 24

†Conventional tillage treatment.
‡Performed the previous fall.

Deere Model 7200 MaxEmerge[1] vacuum planter. Residue managers were engaged for the NT treatments in the 2002 growing season to help improve seed placement in high-residue areas that had decreased stand establishment in the 2001 season. Each year soybean seeds were inoculated with *Bradyrhizobium japonicum* at the time of planting. "Bentazon" [3-(1-methylethyl)-(1H)-2,1,3-benzothiadiazin-4(3H)-one 2,2-dioxide] 42% active ingredient and "Pinnacle" [3-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]amino]sulfonyl]-2-thiophenecarboxylic acid] 25% active ingredient were applied to all plots at rates of 0.29 and 0.003 liters ha^{-1}, respectively, for weed control. Crop planting, tillage, herbicide application, biomass, soil sampling and grain harvest dates are reported in Table 1. Phenology data according to Ritchie et al. (1996) were recorded weekly from the first of June until the end of August.

Plant samples were taken from a 1 m row at R1 and R7 (beginning maturity) growth stages for biomass determination. Samples were dried for 120 h in a forced-air oven at 60°C, weighed, and ground to pass a 2 mm sieve. Plant N concentration was determined on all samples using dry-combustion techniques (Schepers et al., 1989). Total plant N uptake, expressed on a kilogram-per-hectare^{-1} basis, was estimated by multiplying plant N concentrations and dry plant biomass per hectare. Ureide concentration (Patterson et al., 1981) and nitrate concentration (Catalado et al., 1975) were also determined on all samples. Relative abundance of ureide, in proportion to nitrate, was determined using

[1]Mention of trade name or commercial products in this publication is solely for the purpose for providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

the following equation:

$$\text{Relative ureide} = [\text{ureide concentration}/(\text{ureide concentration} + \text{nitrate concentration})] \times 100 \quad (1)$$

Grain yield was estimated by harvesting 15 m of the center two rows from each plot using a plot combine (Massey Ferguson, Haven, KS). Grain moisture and test weights were determined. Soybean grain yield was adjusted to 130 g kg^{-1} moisture. Grain samples were oven-dried at 60°C, ground to pass a 2 mm mesh sieve, and analyzed for N concentration as described above. Whole-bean analysis for oil concentration was determined using near-infrared reflectance spectroscopy (Foss, NIRSystems, Model 5000, Eden Prairie, MN). Calibration equations used to determine oil concentration have a standard error of 0.05%.

Residual soil nitrate was measured at the beginning of each growing season during the three years of the experiment. Soil samples were collected prior to seedbed preparation each year (Table 1). Two soil cores per plot (4.45 cm diameter) were taken to a depth of 60 cm and split into four increments: 0–15, 15–30, 30–45, and 45–60 cm. Soil samples were air-dried at ambient temperature and ground to pass a 2 mm screen. Samples were extracted using 2 *M* KCl (Bremner, 1965) and analyzed for NO_3-N using automated-flow injection analysis (Latchat Instruments, 1989).

Statistical analysis of data within years was performed using the Proc Mixed procedures in SAS (SAS Institute, 1999) utilizing P value = 0.05. Analysis was performed by year due to the significant difference between years.

RESULTS AND DISCUSSION

Plant Biomass

Tillage affected biomass production at the R1 stage in 2001 and 2002, with CT producing greater average biomass than NT (Tables 2 and 3). The greater biomass production under the CT treatment may be attributed to earlier seedling emergence than under the NT treatment. Soil temperatures are typically lower under no-till soil management, leading to slower emergence (Swan et al., 1996). Plants under the NT treatment were able partially to overcome this delay in emergence and slow initial growth by the R7 growth stage. The lack of growth difference due to tillage in 2000 can be attributed to the fact that the NT treatments were established with tillage ending in the spring of 2000 prior to soybean planting.

Nitrogen at planting significantly affected biomass production in all years and development stages (Tables 2 and 3). There was a linear effect on biomass production with N application in all years and sampling dates except at the

R7 growth stage in 2002. These results confirm the findings of Starling et al. (1998), who demonstrated that N applied at planting increased soybean biomass at the R1 growth stage. The R1 sampling date in 2000 was the only date with a significant difference in biomass due to N source (Table 2 and 3).

Overall, biomass production was greater for 2000 compared with 2001 and 2002 and was likely due to rainfall timing and total precipitation (Tables 3 and 4). Total precipitation for 2000 was 333 mm compared with 226 mm for 2001 and

Table 2
Soybean biomass, ureide and nitrate concentrations at beginning bloom (R1) and beginning maturity (R7), and significance levels for treatment and treatment interactions using a mixed model, Brookings, SD, 2000–2002

		Biomass					
		R1			R7		
Source	df	2000	2001	2002	2000	2001	2002
Tillage	1	0.5983	0.0814	0.0104	0.9856	0.1743	0.4759
N Rate	3	0.0778	0.0012	0.0857	0.0909	0.0471	0.1922
Tillage × N Rate	3	0.7402	0.0001	0.5632	0.1457	0.1749	0.1417
N Source	1	0.0739	0.8480	0.8923	0.3955	0.2132	0.7095
Tillage × N Source	1	0.7105	0.2993	0.4043	0.8590	0.2109	0.4477
N Rate × N Source	3	0.0301	0.1055	0.1989	0.3897	0.8878	0.2854
Tillage × N rate × N Source	3	0.5366	0.6712	0.3649	0.8922	0.8660	0.1857
		Ureide concentration					
Tillage	1	0.8858	0.3991	0.4480	0.6553	0.0109	0.0564
N Rate	3	0.4279	0.0001	0.0001	0.9542	0.6661	0.1790
Tillage × N Rate	3	0.8065	0.9766	0.4629	0.3131	0.0088	0.1651
N Source	1	0.0326	0.4678	0.0352	0.6928	0.5091	0.2400
Tillage × N Source	1	0.7288	0.2705	0.5402	0.1035	0.8826	0.8843
N Rate × N Source	3	0.1683	0.5646	0.3905	0.2104	0.8636	0.6242
Tillage × N rate × N Source	3	0.8476	0.8554	0.1846	0.7998	0.9077	0.4506
		Nitrate concentration					
Tillage	1	0.1691	0.4949	0.0481	0.6824	0.9357	0.1894
N Rate	3	0.0134	0.0133	0.0028	0.3001	0.2962	0.9166
Tillage × N Rate	3	0.1783	0.0351	0.2597	0.3014	0.0056	0.8685
N Source	1	0.9062	0.4613	0.3144	0.4144	0.7164	0.7857
Tillage × N Source	1	0.3870	0.0359	0.0006	0.4833	0.3181	0.9969
N Rate × N Source	3	0.2886	0.1595	0.9307	0.7188	0.8397	0.9904
Tillage × N rate × N Source	3	0.9233	0.4652	0.0009	0.8456	0.3859	0.8598

df—degrees of freedom; Pr > F—probability of obtaining a greater F value.

Table 3
Biomass at beginning bloom (R1) and beginning maturity (R7) at Brookings, SD, 2000–2002

	Biomass (kg ha^{-1})					
	2000		2001		2002	
Tillage	R1	R7	R1	R7	R1	R7
CT	921	5667	677	4960	661	4681
NT	907	5662	586	4720	478	4464
Pr > F	0.5983	0.9856	0.0814	0.1743	0.0104	0.4759
N Rate, kg N ha^{-1}	R1	R7	R1	R7	R1	R7
0	912	5530	580	4645	524	4702
8	864	5469	605	4675	552	4500
16	935	5862	662	4899	614	4649
24	944	5798	679	5139	588	4439
Pr > F$^{\pm}$	0.0778	0.0909	0.0012	0.0471	0.0857	0.1922
N Source	R1	R7	R1	R7	R1	R7
AN	893	5610	633	4925	571	4554
UR	935	5720	630	4754	568	4590
Pr > F	0.0739	0.3955	0.8480	0.2132	0.8923	0.7095

CT—conventional tillage; NT—no tillage; AN—ammonium nitrate; UR—urea;

$^{\pm}$—Linear response to applied N.

Each value represents an average of four replications and four N rates or two N sources.

393 mm for 2002. A total of 183 mm rain was received in the last two weeks of August 2002, which was too late in the growing season to influence positively biomass production. Thus, in 2002, only 211 mm of rain was available to influence in-season soybean growth (Table 4).

Residual Soil Nitrate

Initial surface (0–15 cm) soil chemical and physical characteristics as measured by the South Dakota State Soil Testing Laboratory, Brookings, SD (Gelderman et al., 1995), were a pH of 6.3 (1:1 soil:water paste), organic matter of 2.9% (determined by loss on ignition), extractable P of 5 mg kg^{-1}, and extractable K of 181 mg kg^{-1}. Initial subsurface (15–30 cm) soil characteristics were pH of 6.96, organic matter of 2.1%, residual soil nitrate of 6 mg kg^{-1}, extractable P of 2 mg kg^{-1}, and extractable K of 159 mg kg^{-1}. Extractable P (Olsen P) was determined using the $NaHCO_3$ method (Olsen et al., 1954). Extractable K was determined using the NH_4Ac method (Brown and Warncke, 1988).

Table 4
Average monthly temperature, total monthly precipitation, and pan evaporation, Brookings, SD, 2000–2002

	2000			2001			2002		
Month	Temp °C	Precipitation mm	Evaporation mm	Temp °C	Precipitation mm	Evaporation mm	Temp °C	Precipitation mm	Evaporation mm
May	14.3	171	173	14.4	49	156	10.9	78	205
June	18.0	76	177	19.1	93	221	20.8	62	204
July	21.2	45	174	22.8	66	211	24.0	71	231
August	20.7	41	172	21.6	18	224	20.2	183	172
Total Deficit			−363			−586			−418

Total Deficit = precipitation − pan evaporation.

Soil samples were collected each spring prior to planting to establish initial soil-nitrate levels to evaluate the impact of previous crop and management on the soybean growth and development (Table 1). Residual soil nitrate in the top 60 cm did not differ among treatments each year (data not shown). Only surface-soil nitrate in 2002 was significantly affected by N rate ($p = 0.001$), with soil nitrate levels increasing with increasing N rate (14.3, 18.1, 19.7, and 22.3 kg ha^{-1} for the 0, 8, 16, and 24 kg N ha^{-1} rates, respectively). These residual soil-nitrate levels likely influenced plant biomass accumulation and plant nitrate concentrations at R1. However, because levels did not exceed 30 kg ha^{-1} in the top 0–15 cm across all treatments in our study, it is unlikely that this level of residual soil nitrate prevented a positive response to added fertilizer N and that these low levels of soil nitrate impacted biomass production, ureide and nitrate concentrations at the later growth stages, and/or grain yield. Previous research has documented that yield responds to fertilizer N only when soil nitrate is >190 kg ha^{-1} (Stone et al., 1985; Scharf and Wiebold, 2003).

Plant Nitrogen Components

Fixed N in soybean plants is transported in the form of ureide (Harper, 1987), while soil-derived N is transported in the nitrate form. Thus, relative ureide, which was calculated based on ureide and nitrate concentrations, was utilized as a measure of N fixation (Herridge and Peoples 1990). In our study, the impact of independent treatment effects on soybean N fixation was estimated by measuring total plant N, ureide, and nitrate concentrations.

Differences in plant N components (ureide and nitrate) were observed for the early growth stage (R1), while there was no significant difference in plant N components for the later R7 growth stage (Table 2). A minimal difference in plant ureide and nitrate measurements was observed due to tillage in 2001 and 2002, along with a two-way interaction between tillage and N rate in 2001 for both ureide and nitrate concentrations (Tables 2 and 5).

Plant ureide concentration was significantly greater when starter N was applied as UR compared with AN at the R1 (beginning bloom) stage when planted in mid-May (as in 2000 and 2002) compared with late May (as in 2001; Table 5). The planting date in 2001 was May 30, when surface soil temperatures were greater (16.2°C at 15 cm) than at the mid-May planting in 2000 and 2002 (May 15 and 22, respectively) when soil temperatures were 12.2 and 8.5°C at 15 cm, respectively. These initial soil temperatures coupled with average surface-soil temperatures (15 d) following planting— which were 17.5°C in 2001 compared with 13.1°C and 10.3°C in 2000 and 2002, respectively— could have contributed to the difference in response to fertilizer sources. Urea must be transformed into the ammonium form before it can be taken up by the plant (Tisdale et al., 1993). Therefore, cooler soil conditions at the time of planting could have delayed this transformation, thus limiting the availability of urea-N

Table 5
Soybean plant ureide concentrations by N source at R1 (beginning bloom) and by tillage at R7 developmental stages, Brookings, SD, 2000–2002

	Ureide Concentration, mg kg^{-1}		
	2000	2001	2002
N Source		R1	
AN	4024	2314	3360
UR	4693	2171	3791
Pr > F	0.0326	0.4678	0.0352
Tillage		R7	
CT	2843	2583	4602
NT	3019	4096	6651
Pr > F	0.6553	0.0109	0.0565

CT—conventional tillage; NT—-no tillage; AN—ammonium nitrate; UR—urea.

and increasing the need for the plant to fix N. This contention is supported by our results, which demonstrate an increased concentration of ureide in the plant for treatments fertilized with UR compared with the readily available AN source (Table 5). This interpretation agrees with the work of other researchers who reported that soybean nodules were negatively affected by application of N as nitrate-based fertilizers compared with UR or strictly ammonium-based N fertilizers (Uziakowa, 1959).

Plant N concentration was significantly affected by N rate for 2000 and 2002, but not in 2001, although there appeared to be no consistent relationship between plant N concentration and fertilizer N rate among the three growing seasons (Figure 1a). Increasing fertilizer N rate resulted in increased total plant N uptake for all growing seasons, with 2000 and 2001 having a significant response (Figure 1b).

Plant ureide concentration decreased with increasing N rate for the R1 sampling date (Figure 2a). There were no significant differences in ureide concentration for the R7 sampling date due to different N source or N rate. These results agree with Diatloff et al. (1991), who found that application of fertilizer N depressed ureide levels when sampling occurring 48 d after planting (early flowering), but not when sampling occurred 83 d following planting (after flowering).

Ureide concentration at the R7 growth stage (beginning maturity) was significantly affected by tillage in 2001 and 2002, with the NT treatments resulting in a greater ureide concentration compared with the CT (Table 5). Our results agree with those of Harper et al. (1989), who found that N fixation for CT systems was less than half that of the NT systems. The lack of difference in 2000 could again be attributed to tillage ending on the NT treatment prior to the 2000 soybean planting.

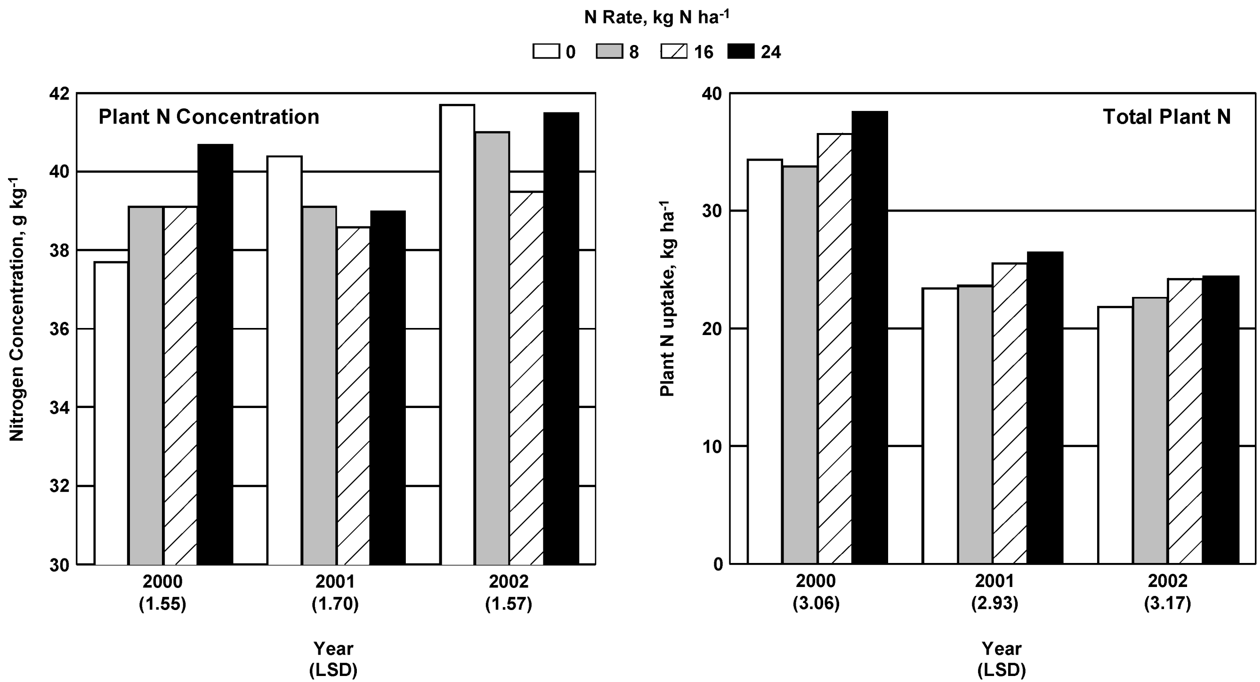

Figure 1. Soybean plant N concentration and total plant N uptake responses to N rate averaged across tillage treatments and N sources at the R1 (beginning bloom) growth stage, Brookings, SD, 2000–2002. Numbers in parentheses represent least-square difference between two treatment means.

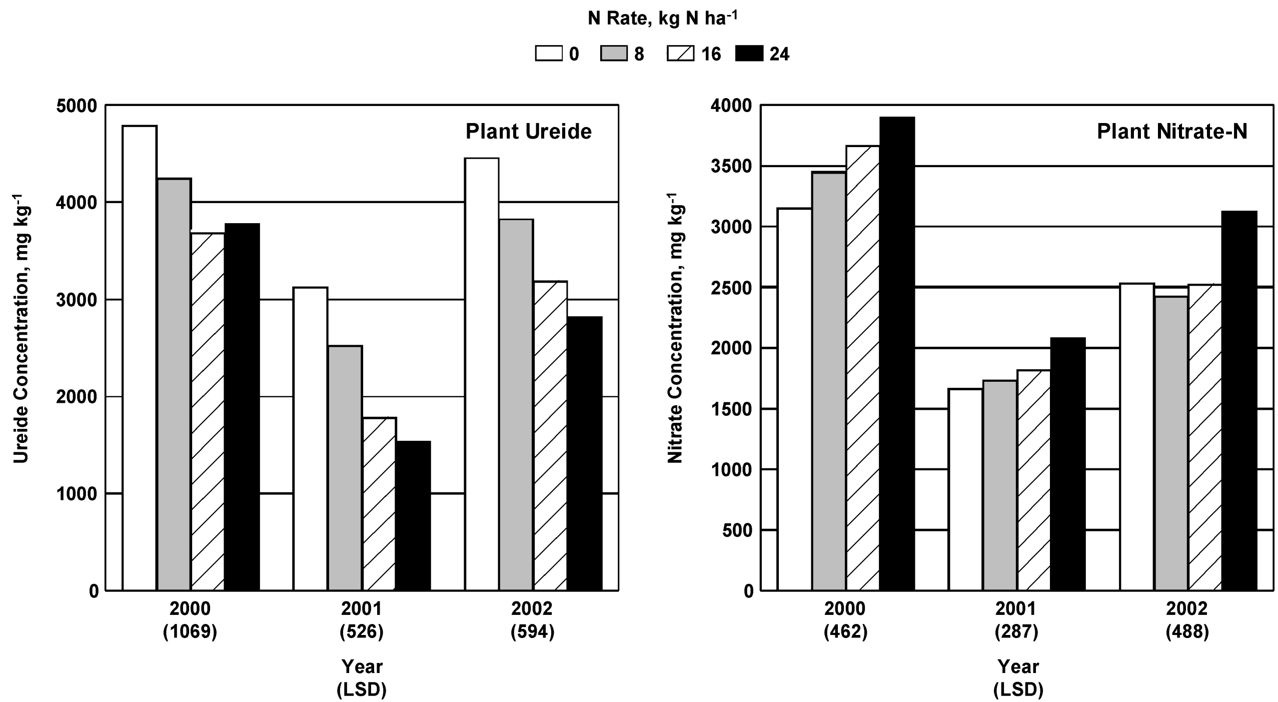

Figure 2. Ureide and nitrate concentrations in soybean plants in response to fertilizer N-rate treatments. Values represent averages over tillage treatments and N sources, Brookings, SD, 2000–2002. Numbers in parentheses represent least-square difference between two treatment means.

Differences in plant nitrate concentrations due to N rate were found at R1 in all three years. Nitrate concentration increased with increasing N rate regardless of N source or tillage (Figure 2b). There was no significant difference in residual soil nitrate for the 2000 and 2001 growing season; therefore, it is likely that differences in plant nitrate concentration were due to fertilizer N applications. Meanwhile, the significant difference in residual soil N in the 2002 growing season could have had an impact on plant nitrate concentration.

Analysis of relative ureide data revealed that there were no significant differences caused by N source and tillage, and that there were no two-way or three-way interactions for any of the sampling dates or years. However, relative ureide did decrease in response to increasing amounts of N fertilizer applied to the soil regardless of N source or tillage practices for all three growing seasons when measured at the R1 growth stage (Figure 3). The highest relative ureide content was approximately 65% for the no-fertilizer treatment and as low as 42% for the 24 kg N ha^{-1} treatment, indicating that there was a greater

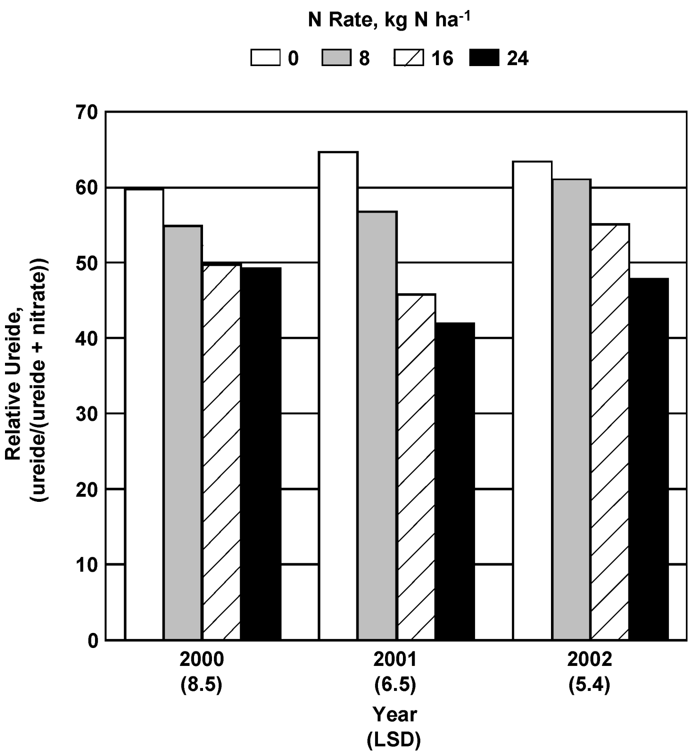

Figure 3. Relative ureide response to N rate averaged over tillage treatments and N sources, Brookings, SD, 2000–2002. Numbers in parentheses represent least-square difference between two treatment means.

amount of N fixation for the no-fertilizer treatment compared with the higher N rates (Figure 3). No significant N rate, N source, tillage, or treatment interaction effects occurred for the R7 growth stage. Average relative ureide values approached 90% (data not shown), indicating that at R7 (beginning bloom) a larger proportion of plant N was derived from N fixation compared with the earlier R1 sampling date.

Grain Yield and Quality

The tillage treatment affected yield in both the 2000 and 2001 growing seasons (Table 6). Grain yield was not affected by tillage in the 2002 growing season (Table 6). There was no significant two-way (tillage × N rate or tillage × N source) or three-way (tillage × N rate × N source) interaction on grain yield in 2001 and 2002. Significant differences in grain yield due to N fertilization rate, N source, and a significant two-way (N rate × N source; $p = 0.0001$) interaction were present in 2000, which corresponded to a difference in biomass production for the same year and treatment interaction. In two of the three years of the study, there was a significant difference in grain yield due to starter-fertilizer application (Table 6). Nitrogen-rate treatment effect was not significant in the 2001 growing season, due possibly to a later planting date compared with the 2000 and 2002, growing seasons. The planting date for the 2001 season was May 30, when soil temperatures were higher (16.2°C at 15 cm) compared with the mid-May planting date (Table 1) for 2000 and 2002, when soil temperatures were lower (12.2 and 8.5°C at 15 cm, respectively). Warmer soil temperatures in 2001 could have caused faster nodulation, allowing plants to fix atmospheric

Table 6
Soybean yield, N and oil concentration, and significance levels for treatment and treatment interactions using a mixed model, Brookings, SD, 2000–2002

		Grain yield			N concentration			Oil concentration		
Source	df	2000	2001	2002	2000	2001	2002	2000	2001	2002
						Pr > F				
Tillage	1	0.0100	0.0221	0.6336	0.1106	0.2232	0.0355	0.0201	0.7522	0.0939
N Rate	3	0.0001	0.1334	0.0683	0.0001	0.3255	0.6821	0.0020	0.4070	0.0001
Tillage × N Rate	3	0.7562	0.3436	0.7546	0.7817	0.6897	0.1378	0.0123	0.3862	0.0013
Source	1	0.0009	0.0059	0.7480	0.0070	0.8630	0.3302	0.5685	0.6757	0.2789
Tillage × Source	1	0.5821	0.8213	0.1104	0.0017	0.8413	0.1936	0.0098	0.9827	0.2105
N Rate × Source	3	0.0001	0.1786	0.4973	0.0233	0.9950	0.1837	0.0061	0.3896	0.5920
Tillage × N Rate × Source	3	0.0845	0.6128	0.7123	0.2492	0.3762	0.3983	0.1589	0.1088	0.8321

df—degrees of freedom; Pr > F—probability of obtaining a greater F value.

N earlier than in 2000 and 2002. Thus, plants in 2000 and 2002 may have been more dependent on fertilizer-applied N than plants in 2001. Research by Ham et al. (1973) found response of soybean to applied N was dependent on environmental conditions, with locations receiving adequate rainfall responding to N compared and locations not receiving adequate rainfall not responding to applied N. Similar to biomass, average grain yield was higher in 2000 than in 2001 and 2002 due to environmental conditions (Table 4).

Soybean grain quality was determined by measuring grain N concentration and oil concentration. In 2000, grain N concentration was significantly affected by N rate and source, while oil concentration was significantly affected by N rate (Table 6). There was also a significant N rate X source interaction for N and oil concentrations in 2000. There were no significant treatment effects on N concentration in the 2001 growing season and only a difference due to tillage for the 2002 growing season (Table 6). Oil concentration was also significantly affected by the main treatment of tillage (CT = 223 g kg^{-1}; NT = 225 g kg^{-1}) with significant tillage × N rate and tillage × N source interactions in the 2000 growing season (Table 6). The tillage × N source interaction results from an increase in oil concentration when plants were fertilized with AN and grown under NT (225 g kg^{-1}) as opposed to CT (223 g kg^{-1}). This same increase was not seen with UR, where the concentration of oil under NT (224 g kg^{-1}) was only slightly higher than that seen under CT (223 g kg^{-1}). There were no treatment effects on oil concentration during the 2001 growing season (Table 6).

CONCLUSIONS

Biomass production was stimulated by application of N at planting, as illustrated by the increase in plant biomass at beginning bloom (R1) and beginning maturity (R7), which also lead to an increased in grain yield when planting occurred in mid-May. Nitrogen applied at planting decreased N fixation at the R1 sampling date as, illustrated by lower plant ureide concentrations and relative ureide content as fertilizer N rate increased. Ureide concentrations were lower when fertilizer N was applied as AN compared with UR when planting occurred in early to mid-May when soil temperatures were cool. No-tillage soil management led to less biomass production at R1 and also greater ureide concentration at R7. However, although application of N fertilizer at planting resulted in lower relative ureide (an estimate of N fixation) at beginning bloom (R1), biomass production increased with application of N fertilizer. Whereas, at the R7 growth stage, there was no difference in N fixation regardless of N rate or source, but the biomass production and grain yield were greater with application of N. The largest difference in yield was obtain for the 2000 growing season, during which soybean was planted in mid-May with the best in-season climatic conditions (timely in-season precipitation) compared with the following years. Grain yield was significantly increased by application of starter N in two (2000 and 2002) out of the three years, coinciding with early planting dates (mid-May compared with late May). Grain yields were increased by an average of 6% for the 16 kg N ha^{-1} rate compared with the no-N treatment. Similar to grain yield, soybean quality was more affected under favorable environmental conditions compared with unfavorable conditions. The relationship between soybean N and oil concentration was inversely related; If soybean N concentration increased due to N fertilization, there was a negative impact on oil concentration. The small differences in yield and quality obtained in this study may not be sufficient to offset additional fertilizer cost if starter fertilizer is not currently applied. However, it is important to note the potential benefit of N applied at planting if the proper environmental conditions exist, or if application of starter is within the current management practice, considering that the additional cost of adding N to a P and K starter application is minimal.

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